

The Benchmark Eclipsing Binary V530 Ori: A Critical Test of Magnetic Evolution Models for Low-Mass Stars

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Abstract. We report accurate measurements of the physical properties (mass, radius, temperature) of components of the G+M eclipsing binary V530 Ori. The M-type secondary shows a larger radius and a cooler temperature than predicted by standard stellar evolution models, as has been found for many other low-mass stars and ascribed to the effects of magnetic activity and/or spots. We show that models from the Dartmouth series that incorporate magnetic fields are able to match the observations with plausible field strengths of 1-2 kG, consistent with a rough estimate we derive for that star.

1. Introduction

It has been known since the 1970's that many low-mass stars in eclipsing binaries tend to exhibit larger radii and cooler temperatures than predicted by standard models of stellar evolution (for a recent review, see Torres 2013) (or Feiden's review in this volume). This phenomenon is widely believed to be the result of stellar activity (magnetic fields and/or spots). Efforts to understand the anomalies by incorporating magnetic

fields into the stellar evolution models have made good progress in the last decade or so (e.g., Mullan & MacDonald 2001; Chabrier et al. 2007; Feiden & Chaboyer 2012), indicating such models are capable of producing “radius inflation” and “temperature suppression” of approximately the right magnitude to explain the observed deviations. However, more quantitative comparisons are generally difficult because the ages and chemical composition of the low-mass stars in eclipsing binaries with well measured masses, radii, and effective temperatures are typically unknown, as are the magnetic field strengths of the components.

Here we present an analysis of the eclipsing binary system V530 Ori, composed of a G-type primary star and an M-type secondary in a 6.11-day orbit. This combination presents a number of advantages: the solar-type primary facilitates the measurement of the metallicity and other characteristics of the system, and while faint (only 1–2% of the flux of the primary), the low-mass secondary is still detectable spectroscopically and allows an accurate measurement of its fundamental properties. Most other well-studied eclipsing binaries with low-mass stars contain two M dwarfs, which makes it challenging to establish the metallicity given the complicated nature of M-star spectra.

2. Observations

Extensive spectroscopy of V530 Ori was obtained using three different telescope and instrument setups at the Harvard-Smithsonian Center for Astrophysics and at the Kitt Peak National Observatory from 1996 to 2014, totaling 145 high-resolution spectra. Radial velocities for both components were measured using the two-dimensional cross-correlation technique TODCOR (Zucker & Mazeh 1994), in the same manner as described recently by Sandberg Lacy et al. (2014).

More than 8000 differential V-band photometric observations of V530 Ori were collected with two robotic telescopes (URSA and NFO) from 2001 to 2012, operating at the University of Arkansas and in New Mexico (USA), respectively. The telescopes, instrumentation, data acquisition and reduction have been described by Grauer et al. (2008) and Sandberg Lacy et al. (2012). We additionally obtained 720 *uvby* measurements with the Strömgren Automatic Telescope at ESO (La Silla, Chile) from 2001 to 2006. A description of the reduction procedures for these observations is given by Clausen et al. (2008).

3. Analysis and Results

The three radial-velocity data sets were combined into a single solution for the spectroscopic elements, after verifying that individual solutions are consistent with each other. The fit indicates the orbit is slightly eccentric ($e = 0.08802 \pm 0.00023$), and gives a mass ratio of $q \equiv M_B/M_A = 0.5932 \pm 0.0022$. Light-curve solutions were performed with the JKTEBOP code (Nelson & Davis 1972; Popper & Etzel 1981; Southworth et al. 2004), and indicate the secondary eclipse is total (totality duration of 70 minutes), and the primary is annular. Our spectroscopic orbital solution and sample fits to the URSA and NFO photometry are shown in Figure 1.

We also subjected the three sets of spectra to disentangling using the FDBINARY program (Ilijic et al. 2004). The disentangled primary spectrum was then analyzed with the UCLSYN package (Smalley et al. 2011) to obtain estimates of the primary temper-

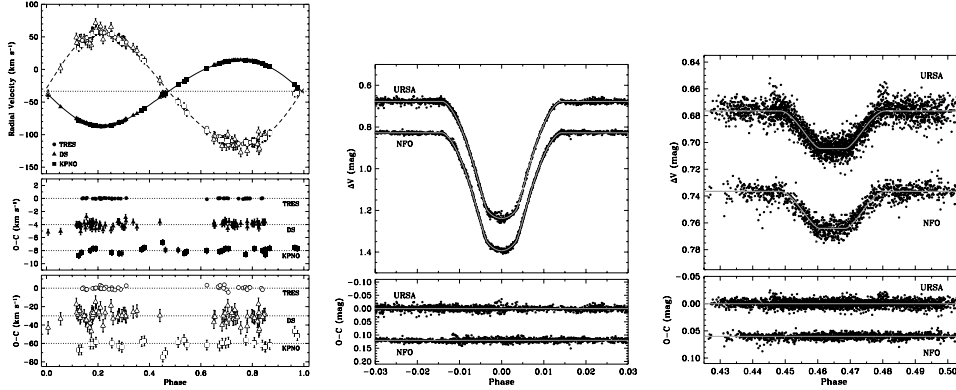


Figure 1. *Left*: Measured radial velocities and combined spectroscopic orbital solution, with residuals shown at the bottom; *Middle and right*: URSA and NFO photometric observations near the primary (middle) and secondary (right) eclipses, along with our best fit model. Residuals are displayed at the bottom.

ature as well as chemical abundances of iron, $[\text{Fe}/\text{H}] = -0.12 \pm 0.08$, and 20 other elements. Several other spectroscopic estimates of the primary temperature are in good agreement. The secondary temperature was derived on the basis of the primary value and the central surface brightness ratio inferred from the light curve analysis. The final absolute dimensions of the system are presented in Table 1, and show that the masses and radii are good to about 1%. The primary star is very similar in mass to the Sun.

Table 1. Physical properties of the components of V530 Ori.

Parameter	Star A	Star B
Mass (M_{\odot})	1.0038 ± 0.0066	0.5955 ± 0.0022
Radius (R_{\odot})	0.980 ± 0.013	0.5873 ± 0.0067
$\log g$ (cgs)	4.457 ± 0.012	4.676 ± 0.010
T_{eff} (K)	5890 ± 100	3880 ± 120
$\log L/L_{\odot}$	0.016 ± 0.032	-1.154 ± 0.053
M_V (mag)	4.71 ± 0.10	8.72 ± 0.11
$E(B - V)$ (mag)	0.045 ± 0.020	
Distance (pc)	103 ± 6	
$[\text{Fe}/\text{H}]$	-0.12 ± 0.08	

4. Stellar Evolution Models and Magnetic Fields

A comparison of the measured masses, radii, and temperatures of both stars with standard (non-magnetic) isochrones from the Dartmouth series (Dotter et al. 2008) for the measured metallicity shows excellent agreement for the primary at an age of about 3 Gyr, but not for the secondary, which appears larger than predicted by $\sim 3.7\%$ and cooler by $\sim 4.8\%$ (see Figure 2, left). Good agreement for the primary is also seen with the Yonsei-Yale models (Yi et al. 2001; Demarque et al. 2004).

An example of a comparison with Dartmouth models that incorporate magnetic fields (Feiden & Chaboyer 2013) is presented in the right panel of the figure, using

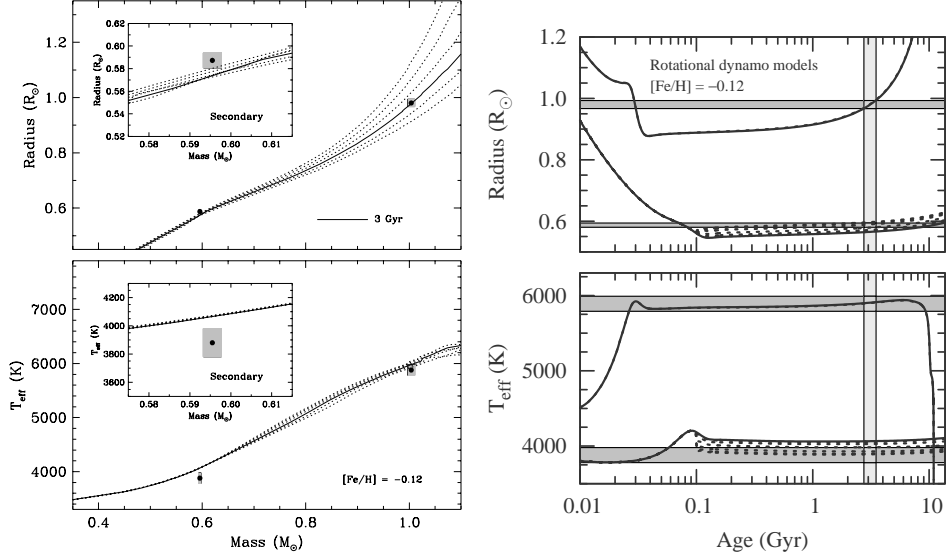


Figure 2. *Left:* Observations for V530 Ori compared against 1–6 Gyr isochrones from the standard Dartmouth models (Dotter et al. 2008) for the measured metallicity. The insets zoom in on the secondary. *Right:* Horizontal bands show the radius and temperature measurements. Solid lines are standard evolutionary tracks from the Dartmouth models for the measured masses, and dotted lines incorporate magnetic fields for the secondary using the rotational dynamo prescription, with field strengths between 0.5 and 3.0 kG.

the rotational or shell dynamo prescription (α – Ω), in which the field is rooted in the strong shear layer at the base of the convective zone (tachocline). We find that with this formulation magnetic fields have relatively little effect on the primary properties for modest magnetic field strengths of ~ 170 G, such as we estimate for this star below, but do allow a good fit to the secondary properties at the same age as the primary for a field strength of $\langle Bf \rangle = 2.1 \pm 0.4$ kG.

An alternate prescription for the secondary using a turbulent or distributed dynamo (α^2) also provides a good match to its properties with a field strength of $\langle Bf \rangle = 1.3 \pm 0.4$ kG, at the same age as the primary. In this case the energy for the magnetic field is drawn from the large-scale convective flow. However, this type of dynamo has a larger effect on the primary properties, such that a 170 G field strength for that star produces a poorer fit to its properties at a somewhat younger age of 2.4 Gyr, and although still possible, reproducing the secondary properties at the same age becomes more difficult.

Are these predicted magnetic field strengths for the secondary plausible? To answer this question, we estimated the field strengths for both stars using an empirical relation between $\langle Bf \rangle$ and the inverse Rossby number proposed by Saar (2001). We assumed the stars are rotationally synchronized, which is reasonable given that the timescale for this phenomenon is much shorter than the age for this system. With Rossby numbers of 0.431 and 0.116 for the primary and secondary based on convective turnover times from the same source used by Saar (2001), we obtained rough $\langle Bf \rangle$ values of 170 ± 140 G and 830 ± 650 G. The latter estimate is indeed consistent with theoretical predictions, within the admittedly large uncertainties.

5. Conclusions

V530 Ori is an important new benchmark eclipsing binary system with accurately measured properties containing a solar-type primary and low-mass secondary displaying radius inflation and temperature suppression, when compared to standard evolution models. Magnetic models are able to match the secondary properties with plausible magnetic field strengths of 1–2 kG, suggesting we are on the right track to understanding these discrepancies. Based strictly on the quality of the fits, the observations seem to suggest a scenario in which magnetic fields have only a minor effect on the solar-mass primary, consistent with it having a rotational dynamo, which is also believed to be mechanism operating in the Sun. The nature of the magnetic field on the secondary is less clear, with the observations perhaps favoring a turbulent (α^2) dynamo over a rotational one, but not at a very significant level.

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